BOREHOLE TELEMETRY SYSTEM

The present invention generally relates to an apparatus and a method for communicating parameters relating to down-hole conditions to the surface. More specifically, it pertains to such an apparatus and method for acoustic communication.

BACKGROUND OF THE INVENTION

One of the more difficult problems associated with any borehole is to communicate measured data between one or more locations down a borehole and the surface, or between down-hole locations themselves. For example, communication is desired by the oil industry to retrieve, at the surface, data generated down-hole during operations such as perforating, fracturing, and drill stem or well testing; and during production operations such as reservoir evaluation testing, pressure and temperature monitoring. Communication is also desired to transmit intelligence from the surface to down-hole tools or instruments to effect, control or modify operations or parameters.

Accurate and reliable down-hole communication is particularly important when complex data comprising a set of measurements or instructions is to be communicated, i.e., when more than a single measurement or a simple trigger signal has to be communicated. For the transmission of complex data it is often desirable to communicate encoded digital signals.

One approach which has been widely considered for borehole communication is to use a direct wire connection between the surface and the down-hole location(s). Communication then

can be made via electrical signal through the wire. While much effort has been spent on "wireline" communication, its inherent high telemetry rate is not always needed and very often does not justify its high cost.

Another borehole communication technique that has been explored is the transmission of acoustic waves. Whereas in some cases the pipes and tubulars within the well can be used to transmit acoustic waves, commercially available systems utilize the various liquids within a borehole as the transmission medium.

Among those techniques that use liquids as medium are the well-established Measurement-While-Drilling or MWD techniques. A common element of the MWD and related methods is the use of a flowing medium, e.g., the drilling fluids pumped during the drilling operation. This requirement however prevents the use of MWD techniques in operations during which a flowing medium is not available.

In recognition of this limitation various systems of acoustic transmission in a liquid independent of movement have been put forward, for example in the US Pat. Nos. 3,659,259; 3,964,556; 5,283,768 or 6,442,105. Most of these known approaches are either severally limited in scope and operability or require down-hole transmitters that consume a large amount of energy.

It is therefore an object of the present invention to provide an acoustic communication system that overcomes the limitations of existing devices to allow the communication of data between a down-hole location and a surface location.

SUMMARY OF THE INVENTION

In accordance with a first aspect of the invention, there is provided an acoustic telemetry apparatus for communicating digital data from a down-hole location through a borehole to the surface comprising an acoustic channel terminated at a down-hole end by a reflecting terminal, an acoustic wave generator located at the surface and providing an acoustic wave carrier signal through said acoustic channel, a modulator to modulate amplitude and/or phase of said carrier wave in response to a digital signal and one or more sensors located at the surface adapted to detect amplitude and/or phase related information of acoustic waves traveling within said acoustic channel.

The new system allows the communication of encoded data that may contain the results of more than one or two different types of measurements, such as pressure and temperature.

The acoustic channel used for the present invention is preferably a continuous liquid-filled channel. Often it is preferable to use a low -loss acoustic medium, thus excluding the usual borehole fluids that are often highly viscous. Preferable media include liquids with viscosity of less than 3×10^{-3} NS/m^2, such as water and light oils.

The modulator includes preferably a Helmholtz-type resonator having an tubular opening to the acoustic channel in the vicinity of the reflecting terminal. The modulator is preferably used to close or open the opening thus changing the phase and/or amplitude of the reflected signal. The

reflecting terminal can have various shapes, including a solid body that closes the acoustic channel, provided it is rigid and therefore constitutes good reflector for the incoming wave.

The acoustic source at the surface preferably generates a continuous or quasi-continuous carrier wave that is reflected at the terminal with controllable phase and/or amplitude shifts induced by the modulator.

In a preferred variant the apparatus may include an acoustic receiver at the down-hole location thus enabling a two-way communication.

The surface-based part of the telemetry system preferably includes signal processing means designed to filter the unreflected (downwards traveling) carrier wave signal from the upwards traveling reflected and modulated wave signals.

To minimize the power consumption of the down-hole apparatus, there are included a further variant of the invention one or more piezoelectric actuators combined with suitable mechanical amplifiers to increase the effective displacement of the actuator system. The energy efficient actuators can be used to control the reflection properties of the reflecting terminal.

Dependence on batteries as source of power for down-hole tools can be further reduced by using an electro-acoustic transducer that regenerates electrical energy from an acoustic wave generated at the surface. This down-hole power generator can be used for various applications, if, however,

used in conjunction with other elements of the present invention, it is advantageous to generate the acoustic wave used to produce power down-hole at a frequency separated from the signal carrier frequency used for telemetry.

In accordance with the yet another aspect of the invention, there is provided a method of communicating digital data from a down-hole location through a borehole to surface, the method comprising the steps of establishing an acoustic channel through the borehole and terminating the channel at a down-hole by a reflecting terminal, generating from the surface an acoustic wave carrier signal within the acoustic channel, modulating amplitude and/or phase of the carrier wave in response to a digital signal and detecting at the surface amplitude and/or phase related information of acoustic waves traveling within the acoustic channel.

In a preferred variant of the invention, the method includes the steps of changing the reflecting properties of the reflecting terminal in order to modulate amplitude and/or phase of the carrier wave.

In yet another preferred variant of the above method, a Helmholtz resonator positioned close to the reflecting terminal is used to modulate the reflecting properties of that terminal.

In a further preferred variant of the invention, a base frequency of the carrier wave is matched to a resonant frequency of the Helmholtz resonator. An approximate match can be performed prior to the deployment of the communication system with the knowledge of the dimension and

other properties of the resonator. Alternatively or additionally, the carrier wave frequency may be tuned after the deployment of the system, preferably through an optimization process involving the step of scanning through a range of possible carrier frequencies and evaluating the signal strength of the modulated reflected wave signal.

It is seen as an advantage of the present invention that a plurality of down-hole measurements can be performed simultaneously with the resulting measurements being encoded into a digital bit stream that is subsequently used to modulate the carrier wave. The modulated carrier wave travels in direction of the surface where it is registered using appropriate sensors.

These and other aspects of the invention will be apparent from the following detailed description of non-limitative examples and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates elements of an acoustic telemetry system in accordance with an example of the invention;

Fig. 2 shows elements of a variant of the novel telemetry system;

FIGs. 3A,B show another telemetry system in accordance with the invention for deployment on coiled tubing during stimulation operations;

FIGs. 4A,B show simulated signal power spectra as received

at a surface location with and without interference of the source spectrum, respectively;

FIGs. 5A,B are flow charts illustrating a tuning method for a telemetry system in accordance with the present invention;

FIG. 6 illustrates an element of a telemetry system in accordance with the present invention with low power consumption;

FIGs. 7A,B are schematic drawings of elements of a down-hole power source; and

FIG. 8 is a flow diagram illustrating steps of a method in accordance with the invention.

EXAMPLES

Referring first to the schematic drawing of FIG.1, there is shown a cross-section through a cased wellbore **110** with a work string **120** suspended therein. Between the work string **120** and the casing **111** there is an annulus **130**. During telemetry operations the annulus **130** is filled with a low-viscosity liquid such as water. A surface pipe **131** extends the annulus to a pump system **140** located at the surface. The pump unit includes a main pump for the purpose of filing the annulus and a second pump that is used as an acoustic wave source. The wave source pump includes a piston **141** within the pipe **131** and a drive unit **142**. Further elements located at the surface are sensors **150** that monitor acoustic or pressure waveforms within the pipe **131** and thus acoustic

waves traveling within the liquid-filled column formed by the annulus **130** and surface pipe **131**.

At a down-hole location there is shown a liquid filled volume formed by a section **132** of the annulus **130** separated from the remaining annulus by a lower packer **133** and an upper packer **134**. The packers **133**, **134** effectively terminate the liquid filled column formed by the annulus **130** and surface pipe **131** as acoustic waves generated by the source **140** are reflected by the upper packer **134**.

The modulator of the present example is implemented as a stop valve **161** that opens or blocks the access to the volume **132** via a tube **162** that penetrates the upper packer **134**. The valve **161** is operated by a telemetry unit **163** that switches the valve from an open to a closed state and vice versa.

The telemetry unit **163** in turn is connected to a data acquisition unit or measurement sub **170**. The unit **170** receives measurements from various sensors (not shown) and encodes those measurements into digital data for transmission. Via the telemetry unit **163** these data are transformed into control signals for the valve **161**.

In operation, the motion of the piston **141** at a selected frequency generates a pressure wave that propagates through the annulus **130** in the down-hole direction. After reaching the closed end of the annulus, this wave is reflected back with a phase shift added by the down-hole data modulator and propagates towards the surface receivers **150**.

The data modulator can be seen as consisting of three parts:

firstly a zero-phase-shift reflector, which is the solid body of the upper packer **134** sealing the annulus and designed to have a large acoustic impedance compared with that of the liquid filling the annulus, secondly a 180-degree phase shifting (or phase-inverting) reflector, which is formed when valve **161** is opened and pressure waves are allowed to pass through the tube **162** between the isolated volume **132** and the annulus **130** and thirdly the phase switching control device **162**, **163** that enables one of the reflectors (and disables the other) according to the binary digit of the encoded data.

In the example the phase-shifting reflector is implemented as a Helmholtz resonator, with a fluid-filled volume **132** providing the acoustic compliance, C, and the inlet tube **162** connecting the annulus and the fluid-filled volume providing an inertance, M, where

[1] $C=V/\rho c^2$

and

[2] $M=\rho L/a$

where V is the fluid filled volume **132**, ρ and c are the density and sound velocity of the filling fluid, respectively, and L and a are the effective length and the cross-sectional area of the inlet tube **162**, respectively. The resonance frequency of the Helmholtz resonator is then given by:

[3] $\omega_0= 1/(MC)^{0.5} = c(a/(LV))^{0.5}$

When the source frequency equals ω_0, the resonator presents its lowest impedance at the down-hole end of the annulus.

When the resonator is enabled, i.e, when the valve **161** is opened, its low impedance is in parallel with the high impedance provided by the upper packer **134** and the reflected pressure wave is phase shifted by approximately 180 degrees, and thus effectively inverted compared to the incoming wave.

The value of ω_0 can range from a few Hertz to about 70 Hertz, although for normal applications it is likely to be chosen between 10 to 40Hz.

The basic function of the phase switching control device, shown as units **163** and **161** in FIG. 1, is to enable and disable the Helmholtz resonator. When enabled, the acoustic impedance at the down-hole end of the annulus equals that of the resonator, and the reflected wave is phase-inverted. When disabled, the impedance becomes that of the packer, and the reflected wave has no phase change. If one assumes that the inverted phase represents binary digit "1", and no phase shift as digit "0", or vice versa, by controlling the switching device with the binary encoded data, the reflected wave becomes a BPSK (binary phase shift key) modulated wave, carrying data to the surface.

The switching frequency, which determines the data rate (in bits/s), does not have to be the same as the source frequency. For instance for a 24Hz source (and a 24Hz resonator), the switching frequency can be 12Hz or 6Hz, giving a data rate of 12-bit/s or 6-bit/s.

The down-hole data are gathered by the measurement sub **170**. The measurement sub **170** contains various sensors or gauges (pressure, temperature etc.) and is mounted below the lower packer **133** to monitor conditions at a location of interest. The measurement sub may further contain data-encoding units and/or a memory unit that records data for delayed transmission to the surface.

The measured and digitized data are transmitted over a suitable communication link **171** to the telemetry unit **163**, which is situated above the packer. This short link can be an electrical or optical cable that traverses the dual packer, either inside the packer or inside the wall of the work string **120**. Alternatively it can be implemented as a short distance acoustic link or as a radio frequency electromagnetic wave link with the transmitter and the receiver separated by the packers **133**, **134**.

The telemetry unit **163** is used to encode the data for transmission, if such encoding has not been performed by the measurement sub **170**. It further provides power amplification to the coded signal, through an electrical power amplifier, and electrical to mechanical energy conversion, through an appropriate actuator.

For use as a two-way telemetry system, the telemetry unit also accepts a surface pressure wave signal through a down-hole acoustic receiver **164**.

A two-way telemetry system can be applied to alter the operational modes of down-hole devices, such as sampling

rate, telemetry data rate during the operation. Other functions unrelated to altering measurement and telemetry modes may include open or close certain down-hole valve or energize a down-hole actuator. The principle of down-hole to surface telemetry (up-link) has already been described in the previous sections. To perform the surface to down-hole down link, the surface source sends out a signal frequency, which is significantly different from the resonance frequency of the Helmholtz resonator and hence outside the up-link signal spectrum and not significantly affected by the down-hole modulator.

For instance, for a 20Hz resonator, the down-linking frequency may be 39Hz (in choosing the frequency, the distribution of pump noise frequencies, mainly in the lower frequency region, need to be considered). When the down-hole receiver **164** detects this frequency, the down-hole telemetry unit **163** enters into a down-link mode and the modulator is disabled by blocking the inlet **162** of the resonator. Surface commands may then be sent down by using appropriate modulation coding, for instance, BPSK or FSK on the down-link carrier frequency.

The up-link and down-link may also be performed simultaneously. In such case a second surface source is used. This may be achieved by driving the same physical device **140** with two harmonic waveforms, one up-link carrier and one down-link wave, if such device has sufficient dynamic performance. In such parallel transmissions, the frequency spectra of up and down going signals should be clearly separated in the frequency domain.

The above described elements of the novel telemetry system may be improved or adapted in various ways to different down hole operations.

In the example of FIG 1, the volume **132** of the Helmholtz resonator is formed by inflating the lower main packer **133** and the upper reflecting packer **134**, and is filled with the same fluid as that present in the column **130**. However as an alternative the Helmholtz resonator may be implemented as a part of dedicated pipe section or sub.

For example in FIG. 2, the phase-shifting device forms part of a sub **210** to be included into a work string **220** or the like. The volume **232** of the Helmholtz resonator is enclosed between a section of the work string **220** and a cylindrical enclosure **230** surrounding it. Tubes **262a,b** of different lengths and/or diameter provide openings to the wellbore. Valves **261a,b** open or close these openings in response to the control signals of a telemetry unit **263**. A packer **234** refects the incoming waves with phase shifts that depend on the state of the valves **261a,b**.

The volume **232** and the inlet tubes **262a,b** are shown pre-filled with a liquid, which may be water, silicone oil, or any other suitable low-viscosity liquid. Appropriate dimensions for inlet tubes **262** and the volume **232** can be selected in accordance with equations [1] - [3] to suit different resonance frequency requirements. With the choice of different tubes **262a,b**, the device can be operated at an equivalent number of different carrier wave frequencies.

In the following example the novel telemetry system is

implemented as a coiled tubing unit deployable from the surface. Coiled tubing is an established technique for well intervention and other operations. In coiled tubing a reeled continuous pipe is lowered into the well. In such a system the acoustic channel is created by filling the coiled tubing with a suitable liquid. Obviously the advantage of such a system is its independence from the specific well design, in particular from the existence or non-existence of a liquid filled annulus for use as an acoustic channel.

A first variant of this embodiment is shown in FIG. 3. In FIG. 3A, there is shown a borehole **310** surrounded by casing pipes **311**. It is assumed that no production tubing has been installed. Illustrating the application of the novel system in a well stimulation operation, pressurized fluid is pumped through a treat line **312** at the well head **313** directly into the cased bore hole **310**. The stimulation or fracturing fluid enters the formation through the perforation **314** where the pressure causes cracks allowing improved access to oil bearing formations. During such a stimulation operation it is desirable to monitor locally, i.e., at the location of the perforations, the changing wellbore conditions such as temperature and pressure in real time, so as to enable an operator to control the operation on the basis of improved data.

The telemetry tool includes a surface section 340 preferably attached to the surface end **321** of the coiled tubing **320**. The surface section includes an acoustic source unit **341** that generates waves in the liquid filled tubing **320**. The acoustic source **341** on surface can be a piston source driven by electro-dynamic means, or even a modified piston pump

with small piston displacement in the range of a few millimeters. Two sensors **350** monitor amplitude and/or phase of the acoustic waves traveling through the tubing. A signal processing and decoder unit **351** is used to decode the signal after removing effects of noise and distortion, and to recover the down-hole data. A transition section **342**, which has a gradually changing diameter, provides acoustic impedance match between the coiled tubing **320** and the instrumented surface pipe section **340**.

At the distant end **323** of the coiled tubing there is attached a monitoring and telemetry sub **360**, as shown in detail in FIG. 3B. The sub **360** includes a flow-through tube **364**, a lower control valve **365**, down-hole gauge and electronics assembly **370**, which contains pressure and temperature gauges, data memory, batteries and an additional electronics unit **363** for data acquisition, telemetry and control, a liquid volume or compliance **332**, a throat tube **362** and an upper control/modulation valve **361** to perform the phase shifting modulation. The electronic unit **363** contains an electromechanical driver, which drives the control/modulation valve **361**. In case of a solenoid valve, the driver is an electrical one that drives the valve via a cable connection. Another cable **371** provides a link between the solenoid valve **365** and the unit **363**.

The coiled tubing **320**, carrying the down-hole monitoring/telemetry sub **360**, is deployed through the well head **313** by using a tubing reel **324**, a tubing feeder **325**, which is mounted on a support frame **326**. Before starting data acquisition and telemetry, both valves **361**, **365** are opened, and a low attenuation liquid, e.g. water, is pumped

through the coiled tubing **320** by the main pump **345**, until the entire coiled tubing and the liquid compliance **332** are filled with water. The lower valve **365** is then shut maintaining a water filled continuous acoustic channel. Ideally the down-hole sub is positioned well below the perforation to avoid high speed and abrasive fluid flow. The liquid compliance (volume) **332** and the throat tube **362** together form a Helmholtz resonator, whose resonance frequency is designed to match the telemetry frequency from the acoustic source **341** on the surface.

The modulation valve **361**, when closed, provides a high impedance termination to the acoustic channel, and acoustic wave from the surface is reflected at the valve with little change in its phase. When the valve is open, the Helmholtz resonator provides a low termination to the channel, and the reflected wave has an added phase shift of close to 180°. Therefore the valve controlled by a binary data code will produce an up-going (reflected) wave with a BPSK modulation.

After the stimulation job, the in-well coiled tubing system can be used to clean up the well. This can be done by opening both valves **361, 362** and by pumping an appropriate cleaning fluid through the coiled tubing **320**.

Coiled tubing system, as described in FIG. 3, may also be used to establish a telemetry channel through production tubing or other down-hole installations.

In the above examples of the telemetry system the reflected signals monitored on the surface are generally small compared to the carrier wave signal. The reflected and

phase-modulated signal, due to the attenuation by the channel, is much weaker than this background interference. Ignoring the losses introduced by the non-ideal characteristics of the down-hole modulator, the amplitude of the signal is given by:

[4] $A_r = A_s 10^{-2\alpha L/20}$

where A_r and A_s are the amplitudes of the reflected wave and the source wave, both at the receiver, α is the wave attenuation coefficient in dB/Kft and $2L$ is the round trip distance from surface to down-hole, and then back to the surface. Assuming a water filled annulus with α =1dB/kft at 25Hz, then for a well of 10kft depth, then $A_r = 0.1A_s$, or the received wave amplitude is attenuated by 20dB compared with the source wave.

The plot shown in FIG. 4A shows a simulated receiver spectrum for an application with 10kft water filled annulus. A carrier and resonator frequency of 20Hz is assumed. The phase modulation is done by randomly switching (at a frequency of 10Hz) between the reflection coefficient of a down-hole packer (0.9) and that of the Helmholtz resonator (-0.8). The effect is close to a BPSK modulation. The background source wave (narrow band peak at 20Hz) interferes with the BPSK signal spectrum which is shown in FIG. 4B.

Signal processing can be used to receive the wanted signal in the presence of such a strong sinusoidal tone from the source. A BPSK signal $v(t)$ can be described mathematically as follows

[5] $v(t) = d(t)A_v \cos(\omega_c t)$

where

$d(t) \in \{+1,-1\}$ = binary modulation waveform

A_v = signal amplitude and

ω_c = radian frequency of carrier wave.

The source signal at the surface has the form

[6] $s(t) = A_s \cos(\omega_c t)$

The received signal $r(t)$ at surface is the sum of the source signal and the modulated signal.

[7]
$$\begin{aligned} r(t) &= d(t)A_v \cos(\omega_c t) + A_s \cos(\omega_c t) \\ &= A_s\left[1 + \frac{A_v}{A_s} d(t)\right]\cos(\omega_c t) \end{aligned}$$

Equation [7] has the form of an amplitude modulated signal with binary digital data as the modulating waveform. Thus a receiver for amplitude modulation can be used to recover the transmitted data waveform *d(t)*.

Alternatively, since the modulated signal and carrier source waves are traveling in opposite directions, a directional filter, e.g. the differential filter used in mud pulse telemetry reception as shown for example in the US Pat. Nos. 3,742,443 and 3,747,059, could be used to suppress the source tone from the received signal. The data could then be recovered using a BPSK receiver.

It is likely that the modulated received signal will be distorted when it reaches the surface sensors, because of wave reflections at acoustic impedance changes along the annulus channel as well as at the bottom of the hole and the surface. A form of adaptive channel equalization will be required to counteract the effects of the signal distortion.

The down-hole modulator works by changing the reflection coefficient at the bottom of the annulus so as to generate phase changes of 180 degrees, i.e. having a reflection coefficient that varies between +1 and -1. In practice the reflection coefficient γ of the down-hole modulator will not produce exactly 180 degree phase changes and thus will be of the form

$$[8]\quad \begin{aligned}\gamma &= G_0 e^{j\theta_0}, \quad d(t)=0 \\ &= G_1 e^{j\theta_1}, \quad d(t)=1\end{aligned},$$

where

G_0 and G_1 are the magnitudes of the reflection coefficients for a "0" and "1" respectively. Similarly, θ_0 and θ_1 are the phase of the reflection coefficients.

A more optimum receiver for this type of signal could be developed that estimates the actual phase and amplitude changes from the received waveform and then uses a decision boundary that is the locus of the two points in the received signal constellation to recover the binary data.

Design tolerances and changes in down-hole conditions such as temperature, pressure may cause mismatch in source and

resonator frequencies in practical operations, affecting the quality of modulation. To overcome this, a tuning procedure can be run after the deployment of the tool down-hole and prior to the operation and data transmission. FIGs. 5A,B illustrate the steps of an example of such a tuning procedure, with FIG. 5A detailing the steps performed in the surface units and FIG. 5B those preformed by the down-hole units.

The down-hole modulator is set to a special mode that modulates the reflected wave with a known sequence of digits, e.g. a square wave like sequence. The surface source then generates a number of frequencies in incremental steps, each last a short while, say 10 seconds, covering the possible range of the resonator frequency. The surface signal processing unit analyzes the received phase modulated signal. The frequency at which the maximum difference between digit "1" and digit "0" is achieved is selected as the correct telemetry frequency.

Further fine-tuning may be done by transmitting frequencies in smaller steps around the frequency selected in the first pass, and repeating the process. During such a process, the down-hole pressure can also be recorded through an acoustic down-hole receiver. The frequency that gives maximum difference in down-hole wave phase (and minimum difference in amplitude) between digit state "1" and "0" is the right frequency. This frequency can be sent to the surface in a "confirmation" mode following the initial tunings steps, in which the frequency value, or an index number assigned to such frequency value, is encoded on to the reflected waves and sent to the surface.

The test and tuning procedure may also help to identify characteristics of the telemetry channel and to develop channel equalization algorithm that could be used to filter in the received signals.

The tuning process can be done more efficiently if a down-link is implemented. Thus once it identifies the right frequency, the surface system can inform the down-hole unit to change mode, rather than to continue the stepping through all remaining test frequencies.

A consideration affecting the applicability of the novel telemetry system relates to the power consumption level of the down-hole phase switching device, and the capacity of the battery or energy source that is required to power it.

In a case where the power consumption of an on-off solenoid valve prevents its use in the down-hole phase switching device, an alternative device can be implemented using a piezoelectric stack that converts electrical energy into mechanical displacement.

In FIG. 6, there is shown a schematic diagram of elements used in a piezoelectrically operated valve. The valve includes stack **61** of piezoelectric discs and wires **62** to apply a driving voltage across the piezoelectric stack. The stack operates an amplification system **63** that converts the elongation of the piezoelectric element into macroscopic motion. The amplification system can be based on mechanical amplification as shown or using a hydraulic amplification as used for example to control fuel injectors for internal

combustion engines. The amplification system **63** operates the valve cover **64** so as to shut or open an inlet tube **65**. The drive voltage can be controlled by a telemetry unit, such as **163** in FIG. 1.

Though the power consumption of the piezoelectric stack is thought to be lower than for a solenoid system, it remains a function of the data rate and the diameter of the inlet tube, which typically ranges from a few millimeters to a few centimeters.

Additionally, electrical coils or magnets (not shown) may be installed around the inlet tube **65**. When energized, they produce an electromagnetic or magnetic force that pulls the valve cover **64** towards the inlet tube **65**, and thus ensuring a tight closure of the inlet.

The use of a strong acoustic source on the surface enables an alternative to down-hole batteries as power supply. The surface system can be used to transmit power from surface in the form of acoustic energy and then convert it into electric energy through a down-hole electro-acoustic transducer. In FIGs. 7A,B there is shown a power generator that is designed to extract electric energy from the acoustic source.

A surface power source **740**, which operates at a frequency that is significantly different from the telemetry frequency, sends an acoustic wave down the annulus **730**. Preferably this power frequency is close to the higher limit of the first pass-band, e.g. 40~ 60 Hz, or in the 2nd or 3rd pass-band of the annulus channel, say 120Hz but preferably

below 200Hz to avoid excessive attenuation. The source can be an electro-dynamic or piezoelectric bender type actuator, which generates a displacement of at least a few millimeters at the said frequency. It could be a high stroke rate and low volume piston pump, which is adapted as an acoustic wave source.

In the example of FIG. 7, the electrical to mechanic energy converter **742** drives the linear and harmonic motion of a piston **741**, which compresses/de-compresses the liquid in the annulus. The source generates in the annulus **730** an acoustic power level in the region of a kilowatt corresponding to a pressure amplitude of about 100psi (0.6 MPa). Assuming an attenuation of 10dB in the acoustic channel, the down-hole pressure at 10Kft is about 30psi (0.2MPa) and the acoustic power delivered to this depth is estimated to be approximately 100W. Using a transducer with mechanical to electrical conversion efficiency of 0.5, 50W of electrical power could be extracted continuously at the down-hole location.

As shown in FIG. 7A, the down-hole generator includes a piezoelectric stack **71**, similar to the one illustrated in FIG. 6. The stack is attached at its base to a tubing string **720** or any other stationary or quasi-stationary element in the well through a fixing block **72**. A pressure change causes a contraction or extension of the stack **71.**This creates an alternating voltage across the piezoelectric stack, whose impedance is mainly capacitive. The capacitance is discharged through a rectifier circuit **73** and then is used to charge a large energy storing capacitor **74** as shown in FIG. 7B. The energy stored in the capacitor **74** provides

electrical power to down-hole devices such as the gauge sub **75**.

The efficiency of the energy conversion process depends on the acoustic impedance match (mechanical stiffness match) between the fluid wave guide **720** and the piezoelectric stack **71**. The stiffness of the fluid channel depends on frequency, cross-sectional area and the acoustic impedance of the fluid. The stiffness of the piezoelectric stack **71** depends on a number of factors, including its cross-section (area) to length ratio, electrical load impedance, voltage amplitude across the stack, etc. An impedance match may be facilitated by attaching an additional mass **711** to the piezoelectric stack **71**, so that a match is achieved near the resonance frequency of the spring-mass system.

FIG. 8 summarizes the steps described above.

While the invention has been described in conjunction with the exemplary embodiments described above, many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure. Accordingly, the exemplary embodiments of the invention set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.